

Neutron Stars in Supernova Remnants
ASP Conference Series, Vol. 999, 2002
P. O. Slane and B. M. Gaensler, eds.

The New Gamma-ray Pulsar PSR J2229+6114, its Pulsar Wind Nebula, and Comparison with the Vela Pulsar

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Abstract. With a period of 51.6 ms and spin-down power 2.2×10^{37} erg s⁻¹, PSR J2229+6114 is a compelling identification for the EGRET source 3EG J2227+6122 in which error circle it resides. Striking features of the *Chandra* X-ray image are an incomplete elliptical arc and a possible jet, similar to the structures that dominate the appearance of the Vela PWN. Approximately 70% of the 2–10 keV X-ray emission comes from a centrally peaked, diffuse nebula of radius 100'' with a power-law spectrum of photon index 1.45 ± 0.19 . The pulsar itself has a marginally harder spectrum with photon index 0.99 ± 0.27 . For an assumed distance of 3 kpc the ratio of X-ray luminosity to spin-down power of PSR J2229+6114 is only 8×10^{-5} . We discuss a model in which such inefficient X-ray emission is the signature of a highly magnetized pulsar wind that prevents an internal MHD shock, at the location of the X-ray arc, from strongly compressing the flow. The incomplete X-ray arc is consistent with beaming from a relativistic equatorial outflow, while a surrounding radio shell is probably the forward shock in the surrounding ISM.

An MeV source at this location was previously detected by the COMPTEL experiment on *CGRO*. This, plus the flat X-ray spectrum in the 2–10 keV band, suggests that PSR J2229+6114 is one of the brightest pulsars at 1 MeV, even while it is inconspicuous at radio through X-ray wavelengths, and as steep as the Crab above 100 MeV. The apparent variety of broad-band spectra displayed by high-energy pulsars bolsters the theory that rotation-powered pulsars dominate the unidentified Galactic EGRET source population.

1. Does PSR J2229+6114 = 3EG J2227+6122?

3EG J2227+6122 (Hartman et al. 1999) is one of many “unidentified” EGRET sources at low Galactic latitude, $(\ell, b) = (106.^\circ 5, 3.^\circ 2)$, for which a pulsar origin is the hypothesis favored by many authors. Halpern et al. (2001a,b) made a complete multiwavelength study of the error circle of 3EG J2227+6122 that culminated in the discovery of a single plausible counterpart, a young, energetic pulsar (Figures 1 and 2) with an associated X-ray PWN (Figure 3) that is confined within a small, nonthermal radio shell. Compared to known γ -ray pulsars PSR J2229+6114 is second only to the Crab in spin-down power, and it is significantly more luminous than the Vela pulsar (PSR B0833–45). For a distance of 3 kpc estimated from X-ray absorption, PSR J2229+6114 ranks #3 or #4

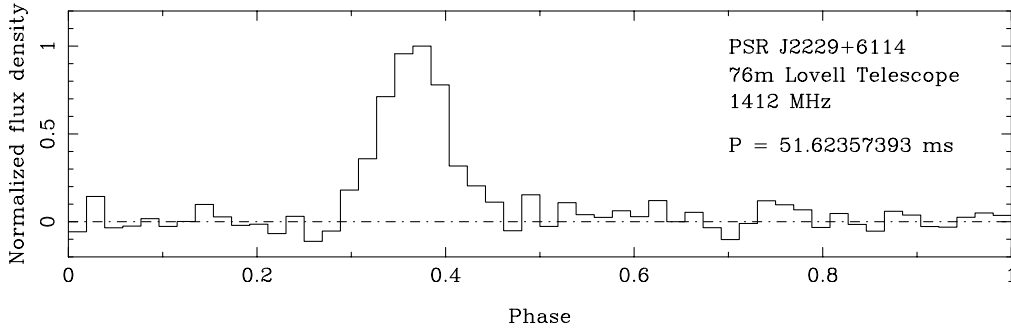


Figure 1. Radio pulse profile of PSR J2229+6114 at 1412 MHz. The instrumental resolution is ≈ 0.02 of the period. Phase zero is arbitrary. The period-averaged flux density is only ≈ 0.25 mJy, consistent with its non-detection in previous “all-sky” pulsar surveys.

among all pulsars in spin-down flux \dot{E}/d^2 . If PSR J2229+6114 is the counterpart of 3EG J2227+6122, then its luminosity above 100 MeV is $\approx 3.7 \times 10^{35}$ erg s $^{-1}$, and its efficiency η of > 100 MeV γ -ray production, if isotropic, is $0.016 (d/3 \text{ kpc})^2$. Among the pulsars that are either reliably or probably identified with EGRET sources (Table 1), there is a trend (e.g., Thompson et al. 1999) in which the efficiency of γ -ray production increases with decreasing spin-down power ($\dot{E} \propto B^2/P^4$), or equivalently, open field line voltage ($\Phi \propto B/P^2$). As the source of 3EG J2227+6122, PSR J2229+6114 would have an efficiency in accord with the established pattern if its distance were close to our estimate of 3 kpc. It’s a pretty good bet that PSR J2229+6114 is responsible for 3EG J2227+6122 even though the EGRET photons are too few and too old for a significant, confirming pulsar detection using the contemporary ephemeris (Thompson et al., these proceedings). If PSR J2229+6114 is not the correct identification, it implies that a highly efficient (or highly beamed) γ -ray source can avoid producing soft or hard X-rays, in this case at a level below 4×10^{-14} erg cm $^{-2}$ s $^{-1}$, or $< 10^{-4}$ of its apparent γ -ray luminosity, which is unprecedented. Taking into account our exhaustive search of the error circle, the conservative conclusion is acceptance of the identification of 3EG J2227+6122 with PSR J2229+6114.

Table 1. EGRET PULSARS

Name	Period (s)	Age ($P/2\dot{P}$) (yr)	Dist. (pc)	$\dot{E} = I\Omega\dot{\Omega}$ (erg s $^{-1}$)	η (> 100 MeV)
Crab	0.033	1,250	2,000	5.0×10^{38}	0.002
PSR J2229+6114	0.051	10,500	3,000	2.2×10^{37}	0.016
Vela	0.089	11,200	250	6.3×10^{36}	0.008
PSR B1951+32	0.039	107,000	2,400	3.7×10^{36}	0.03
PSR B1706-44	0.102	17,400	1,800	3.4×10^{36}	0.09
PSR B1046-58	0.124	20,400	3,000	3.1×10^{36}	0.14
Geminga	0.237	340,000	160	3.3×10^{34}	0.20
PSR B1055-52	0.197	540,000	1,500	3.0×10^{34}	~ 1

2. X-ray Pulsar and Nebula

The sharp main pulse with fast rise time in Figure 2 is indicative of nonthermal magnetospheric emission. The weaker interpulse is equally prominent at soft and hard energies. That the soft and hard X-ray pulse shapes of PSR J2229+6114 are the same within errors can be interpreted as absence of evidence for a separate component of surface thermal emission. Although the *ASCA* GIS source is dominated by an unknown amount of extended emission (Halpern et al. 2001a), the subsequent observation by the *Chandra* ACIS-I revealed that approximately 70% of the 2–10 keV X-ray emission comes from a centrally peaked, diffuse nebula of radius $100''$ (Halpern et al. 2001b). The diffuse X-rays are apparently confined within the radio shell of similar radius discussed in the next section. The nebula has a power-law spectrum of photon index $\Gamma = 1.45 \pm 0.19$. The pulsar itself has a marginally harder spectrum with photon index $\Gamma = 0.99 \pm 0.27$, and unabsorbed 2–10 keV flux 4.9×10^{-13} erg cm $^{-2}$ s $^{-1}$. These fits are consistent with the *ASCA* measured $\Gamma = 1.51 \pm 0.14$ for the entire blended structure, and the *ASCA* value of $N_{\text{H}} = (6.3 \pm 1.3) \times 10^{21}$ cm $^{-2}$ remains the most precise determination of the column density to the pulsar. We use this value of N_{H} to estimate the distance to the pulsar as 3 ± 1 kpc. The distance remains the most important, poorly determined property of PSR J2229+6114. In addition to our X-ray estimate of 3 kpc, values as large as 12 kpc from the radio pulsar dispersion measure of 200 cm $^{-3}$ pc and the Taylor & Cordes (1993) free electron model, to as small as 800 pc from velocity structure in surrounding H I emission (Kothes, Uyaniker, & Pineault 2001; Kothes et al., these proceedings), have been suggested.

Although the short *Chandra* exposure barely reveals the complex structures in the PSR J2229+6114 nebula (Figure 3), there is evidently an incomplete elliptical arc, similar to the structures that dominate the appearance of the prototype of its class, the Vela PWN (Helfand, Gotthelf, & Halpern 2001), and a possible jet seen as a point source $14''$ to the west of the pulsar.

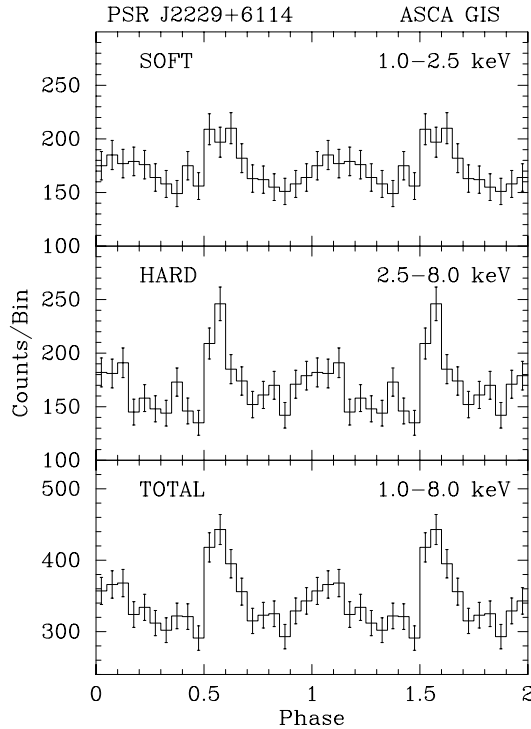


Figure 2. X-ray pulse profile of PSR J2229+6114 from the *ASCA* GIS. The instrumental time resolution is comparable to the width of one phase bin. Un-pulsed flux is dominated by nebular emission.

3. Radio Nebula

The incomplete radio shell that surrounds PSR J2229+6114 is unique in having an extremely flat spectrum, $\alpha_r \approx 0.0$, even though it has shell morphology (see Halpern et al. 2001a for details). It is clearly a non-thermal source, as it is polarized at a level of $\approx 25\%$, but its flat spectrum is not easily understood. We assigned the name G106.6+2.9 to this radio structure. Since the X-ray emission appears to be largely confined within the radio shell, and since the shell is too small ($r \approx 1.5$ pc) to be the blast wave of a 10^4 yr old supernova remnant, we conclude that the radio emission comes from a shock driven into the surrounding medium either by the motion of the pulsar or by the expansion of the PWN. In the bow-shock interpretation, we can relate the spin-down power, $\dot{E} = 2.2 \times 10^{37}$ erg s $^{-1}$ assumed to be carried almost entirely by the PWN, to the velocity of the pulsar v_p , the ambient density n_H , and the radius of the shock r_0 via

$$\dot{E} = 4\pi r_0^2 c \rho_0 v_p^2 = 2.2 \times 10^{37} \left(\frac{n_H}{0.01} \right) \left(\frac{d}{3 \text{ kpc}} \right)^2 \left(\frac{v_p}{90 \text{ km s}^{-1}} \right)^2 \text{ erg s}^{-1}.$$

This would require a low-density medium, as might be appropriate at a z -height of 150 pc or in a cavity previously evacuated by a supernova explosion. Alternatively, confinement of the radio nebula by the *static* pressure of the surround ISM is possible in a higher-density medium if

$$\dot{E} = 4\pi r_0^2 c (n_e + n_i) k T = 2.2 \times 10^{37} \left(\frac{n_H}{0.9} \right) \left(\frac{d}{3 \text{ kpc}} \right)^2 \left(\frac{T}{10^4 \text{ K}} \right) \text{ erg s}^{-1}.$$

In addition to this compact radio nebula, Pineault & Joncas (2000) discovered the larger radio continuum source G106.3+2.7, approximately $0.5^\circ \times 1^\circ$ in extent, which they classified as a supernova remnant. Kothes et al. (2001) regard this structure, which borders on the compact radio nebula G106.6+2.9, as the remnant of the supernova that gave birth to PSR J2229+6114.

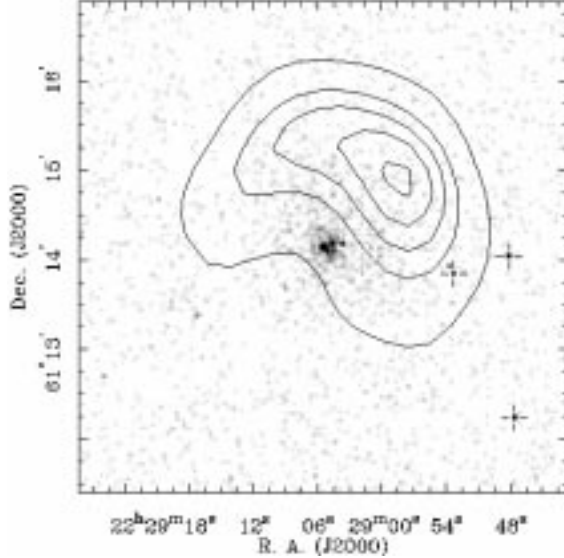


Figure 3. A portion of the *Chandra* ACIS-I image showing PSR J2229+6114 and its associated PWN (*greyscale*). The image is binned into $\approx 1''$ pixels and smoothed with a 3-pixel top-hat filter. The NVSS 20 cm map of the partial shell G106.6+2.9 is overlaid (*contours*).

4. Comparing the PWN of PSR J2229+6114 to Vela's

Morphological similarities between the PSR J2229+6114 and Vela PWNe are the incomplete elliptical arc, which Helfand et al. (2001) interpreted as a cylindrical equatorial shock in the Vela pulsar's wind, and a possible jet, located on the minor axis of the ellipse, assumed to be the projected rotation axis of the pulsar (P.A. 280° in Figure 3). In the context of the Kennel & Coroniti (1984) model, the semi-major axis of the equatorial arc can be interpreted as r_s , the radius of the MHD wind shock, while the radio shell of G106.6+2.9, which is either a bow-shock or a static bubble, coincides with the outer extent of the X-ray synchrotron nebula and denotes r_n . The Vela X-ray PWN is apparently confined by the thermal pressure of its surrounding hot SNR, which gives its X-ray emission a clear discontinuity. In the case of the Crab $r_n/r_s \approx 20$, while for PSR J2229+6114, $r_n/r_s \approx 9$, and Vela has $r_n/r_s \approx 2$. Unlike the Crab Nebula, which is a fairly effective “calorimeter” of the pulsar spin-down power, both PSR J2229+6114 and Vela are characterized by extremely inefficient X-ray emission, $L_x/\dot{E} \approx 8 \times 10^{-5}$ including pulsar and nebula. This could be an indicator of a highly magnetized pulsar wind that prevents an internal MHD shock, at the location of the X-ray arcs, from strongly compressing the flow. Consequently, both the rapid post-shock outflow and the weak post-shock magnetic field prevent the bulk of the wind energy from being radiated away.

In the case of Vela, we have modelled the surface brightness of its X-ray arcs in terms of a standing shock in a relativistic outflow. If we assume that the arcs have cylindrical symmetry, velocities of at least $0.5 - 0.7c$ are required to explain their asymmetric brightness as Doppler boosting in the approaching side of the flow, and dimming of the receding side. If so, the entire postshock flow from r_s to $r_n \approx 2r_s$ must be relativistic, and the magnetization parameter σ , defined as the ratio of Poynting flux to particle flux in the pre-shock pulsar wind, must be of order 0.1 or greater (see Figure 3 of Kennel & Coroniti 1984). In the Crab, of course, the same model yields the small value $\sigma \approx 0.003$, which is consistent with its large value of r_n/r_s and small outflow velocity $v < 0.01c$ at r_n , the outer boundary of the nebula.

While there is much less detailed information about PSR J2229+6114 than either the Crab or Vela, inspection of Figure 3 gives the impression of a significant asymmetry in the brightness of the arc, therefore a high velocity at r_s . A deeper *Chandra* image will be obtained to quantify this effect, but from all appearances, PSR J2229+6114 resembles Vela more than it does the Crab. Its surface brightness declines severely with radius, which may be the result of a post-shock magnetic field that declines as $1/r$ in the limit of large σ . Whereas the values of r_s in Vela (1×10^{17} cm) and PSR J2229+6114 (5×10^{17} cm) scale roughly as the expected $\dot{E}^{1/2}$, we note that $r_n \approx 1.5$ pc in PSR J2229+6114 is a very large value that probably indicates a lower ISM pressure ($< 3 \times 10^{-12}$ dyne cm $^{-2}$) than in the case of the smaller Vela nebula, which is confined by the pressure of its hot surrounding SNR, estimated as 8.5×10^{-10} dyne cm $^{-2}$ (Markwardt & Ögelman 1997; Helfand et al. 2001). Here we have assumed $d = 250$ pc for Vela and $d = 3$ kpc for PSR J2229+6114. However, a more complete understanding of the physics of PSR J2229+6114 and its PWN awaits a reliable determination of its distance, for which estimates ranging from 0.8 to 12 kpc have been suggested, an unacceptably large disagreement.

5. Broad-Band Spectrum of PSR J2229+6114

The γ -ray spectrum of 3EG J2227+6122 is parameterized as a power-law of photon index $\Gamma = 2.24 \pm 0.14$ (Hartman et al. 1999), steep compared to all other EGRET pulsars except the Crab, for which $\Gamma = 2.19 \pm 0.02$. Iyudin et al. (1997) reported a source in the 0.75–3 MeV band with COMPTEL, coincident with 3EG J2227+6122 but with a much larger error box. This detection is consistent in flux with an extrapolation of the EGRET spectrum, but it exceeds an extrapolation of the 2–10 keV spectrum of PSR J2229+6114 to 1 MeV. In Figure 4 we show a schematic representation of the high-energy spectrum of PSR J2229+6114 under the assumption that it is responsible for the coincident EGRET and COMPTEL sources. In comparison with the Crab and Vela, the only other pulsars detected by COMPTEL, we see that PSR J2229+6114 may be one of the brightest in the sky at 1 MeV, even as it is relatively inconspicuous at radio through X-ray wavelengths. This variety of broad-band spectra is encouraging of the hypothesis that new rotation-powered pulsars will be discovered to be responsible for more of the unidentified Galactic EGRET sources.

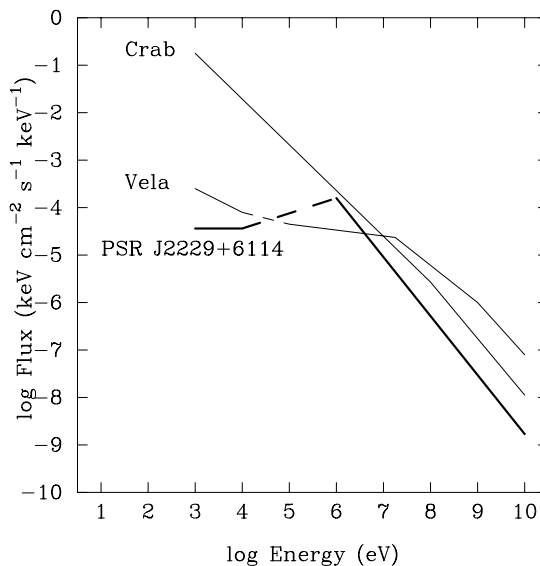


Figure 4. The non-thermal, pulsed components of the three most energetic γ -ray pulsars.

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